

# DNA sequences encoding dystrophin minigenes and methods of use thereof

## TECHNICAL FIELD

5 The present invention relates to novel dystrophin minigenes that retain the essential biological functions of a full length dystrophin gene, and methods of treatment for Duchenne muscular dystrophy (DMD) and Becker muscular dystrophy (BMD) in a mammalian subject using the dystrophin minigenes.

## BACKGROUND OF INVENTION

10 Duchenne muscular dystrophy (DMD) is an X-linked genetic muscle disease affecting 1 of every 3,500 newborn males (Kunkel et al. *Nature* (London) 322,73-77 [1986]). The progressive muscle degeneration and weakness usually confine the patients to wheelchairs by their early teens, and lead to death by their early twenties. DMD is caused by recessive mutations in the dystrophin gene, the largest gene known to date, which spans nearly 3 million base-pairs on the X-chromosome with 79 exons, a coding  
15 sequence of about 11 kb, and a high rate of *de novo* mutations. (Koenig et al. *Cell* 50, 509-517 [1987]).

Dystrophin is an enormous rod-like protein of 3,685 amino acids (aa) localized beneath the inner surface of muscle cell membrane (Watkins, S. C. et al. *Nature* 333, 863-866 [1988]). It functions through four major structural domains: a N-terminal  
20 domain (1-756 aa), a central rod domain (757-3122 aa), a cysteine rich (CR) domain (3123-3409aa), and a distal C-terminal domain (3410-3685 aa). The N-terminal domain binds to the F-actin of cytoskeletal structures, while the CR domain along with the distal C-terminal domain anchors to the cell membrane via dystrophin-associated protein (DAP) complexes, thus, dystrophin crosslinks and stabilizes the muscle cell membrane  
25 and cytoskeleton. The central rod domain contains 24 triple-helix rod repeats (R1-R24) and 4 hinges (H1-H4). Each repeat is approximately 109 aa long. (Koenig et al. *J Biol Chem* 265, 4560-4566 [1990]). The central rod domain presumably functions as a "shock absorber" during muscle contraction. Dystrophin crosslinks and stabilizes the muscle cell membrane and cytoskeleton. The absence of a functional dystrophin results in the loss of  
30 DAP complexes and causes instability of myofiber plasma membrane. These deficiencies in turn lead to chronic muscle damage and degenerative pathology.

The vast majority of DMD mutations disrupt the dystrophin mRNA reading frame or introduce a stop codon that prematurely ends protein translation (Monaco et al. Genomics 2, 90-95 [1988]). In the less severe allelic form of the disease, Becker muscular dystrophy (BMD), dystrophin gene mutations are usually such that the mRNA  
5 reading frame is maintained. Thus in BMD patients, some functional gene product, albeit of reduced quantity and/or quality, is synthesized that contributes to the milder phenotype (Hoffman et al. *N. Engl. J. Med.* 318, 1363-1368 [1988]).

The *mdx* mouse (Bulfield et al. *Proc. Natl. Acad. Sci. USA* 81, 1189-1192 [1984]) is an animal model of DMD. The genetic lesion in the *mdx* dystrophin gene is a  
10 nonsense mutation at base 3185 of the mRNA that causes premature termination of translation within exon 23. This nonsense mutation precludes synthesis of a functional protein.

Due to the lack of effective treatment for DMD, novel genetic approaches including cell therapy and gene therapy have been actively explored. However, clinical  
15 trials of myoblast transplantation have met with little success owing to the poor survival of the transplanted cells (Gussoni et al., *Nature Med* 3, 970-977 [1997]). It was recently reported that gentamicin treatment in *mdx* mice led to the suppression of the premature stop codon in the dystrophin gene, and the subsequent expression and localization of functional dystrophin to the cell membrane (Barton-Davis et al. *J Clin Invest.* 104, 375-  
20 381 [1999]). This treatment could prove effective in up to 15% of patient with DMD.

Somatic gene transfer offers a new approach to replace the defective dystrophin gene. A preferred approach for introducing genetic material encoding a gene product into an organ or a tissue is by use of a viral vector. In this situation, the genetic material encoding the gene product is inserted into the viral genome (or a partial viral genome).  
25 The regulatory elements directing the expression of the gene product can be included with the genetic material inserted into the viral genome (i.e., linked to the gene inserted into the viral genome) or can be provided by the viral genome itself, for example, a retrovirus long terminal repeat (LTR) or an adeno-associated virus (AAV) inverted terminal repeat (ITR). Infection of cells with a viral vector has the advantage that  
30 molecules encoded within the viral vector, e.g., by a cDNA contained in the viral vector, are expressed efficiently in cells which have taken up viral vector nucleic acid and viral

vector systems can be used in vivo. Different viral vectors are described separately in the subsections below.

1. *Adenovirus vectors*: The genome of an adenovirus can be manipulated such that it encodes and expresses a gene product of interest but is inactivated in terms of its ability to replicate in a normal lytic viral life cycle (Curiel, *Ann N Y Acad Sci* 886, 158-71 [1999]). Suitable adenoviral vectors derived from the adenovirus strain Ad type 5 dl324 or other strains of adenovirus (e.g., Ad2, Ad3, Ad7 etc.) are well known to those skilled in the art. Recombinant adenoviruses are advantageous in that they do not require dividing cells to be effective gene delivery vehicles and can be used to infect a wide variety of cell types, including airway epithelium, endothelial cells and muscle cells. Additionally, introduced adenoviral DNA (and foreign DNA contained therein) is not integrated into the genome of a host cell but remains episomal, thereby avoiding potential problems that can occur as a result of insertional mutagenesis in situations where introduced DNA becomes integrated into the host genome (e.g., retroviral DNA). Moreover, the carrying capacity of the adenoviral genome for foreign DNA is large (up to 8 kilobases) relative to other gene delivery vectors (Haj-Ahmand et al. *J. Virol.* 57, 267-273 [1986]). Most replication-defective adenoviral vectors currently in use are deleted for all or parts of the viral E1 and E3 genes but retain as much as 80% of the adenoviral genetic material. Adenoviral vectors deleted for all viral coding regions are also described by Kochanek et al. and Chamberlain et al. (U.S. Pat. No. 5,985,846 and U.S. Pat. No. 6,083,750).

Adenovirus vectors have been successfully tested in dystrophic animal models (Ragot et al. *Nature* 361, 647-50 [1993]; Howell et al. *Hum Gene Ther* 9, 629-34 [1998]). Nonetheless, the immunogenicity and inefficiency of infecting mature muscle cells remain major hurdles to overcome before the adenovirus vectors can be safely used in humans.

2. *Herpes simplex virus (HSV) vectors*: The main feature of an HSV vector is that it has very large packaging capacity, is usually replication defective and does not integrate into the host genome. HSV infects cells of the nervous system (Fink et al. *Annu Rev Neurosci* 19, 265-287, [1996]). The virus contains more than 80 genes, one of which (IE3) can be replaced to create the vector. The generation of HSV vectors with

deletions in many of the immediate early gene products has resulted in vectors with reduced toxicity and antigenicity, as well as prolonged expression in vivo. However, these modifications also result in a lower virus yield. Construction of HSV vectors is described in U.S. Pat. No. 5,661,033.

5           3. *Retrovirus vectors*: Defective retroviruses are well characterized for use in gene transfer for gene therapy purposes (Miller AD *Blood* 76, 271-278 [1990]). The members of the family Retroviridae are characterized by the presence of reverse transcriptase in their virions. There are several genera included within this family, including Cisternavirus A, Oncovirus A, Oncovirus B, Oncovirus C, Oncovirus D, Lentivirus, and  
10 Spumavirus.

A recombinant retrovirus can be constructed having a nucleic acid encoding a gene product of interest inserted into the retroviral genome. Additionally, portions of the retroviral genome can be removed to render the retrovirus replication defective. The replication defective retrovirus is then packaged into virions which can be used to infect a  
15 target cell through the use of a helper virus by standard techniques. Protocols for producing recombinant retroviruses and for infecting cells in vitro or in vivo with such viruses can be found in "Current Protocols in Molecular Biology, Ausubel, F. M. et al. (eds.) Greene Publishing Associates, (1989), Sections 9.10-9.14" and other standard laboratory manuals. Examples of suitable retroviruses include pLJ, pZIP, pWE and pEM  
20 which are well known to those skilled in the art. Examples of suitable packaging virus cell lines include .psi.Crip, .psi.Cre, .psi.2 and .psi.Am.

Retroviruses have been used to introduce a variety of genes into many different cell types, including epithelial cells, endothelial cells, lymphocytes, myoblasts, hepatocytes, hematopoietic stem cells, in vitro, and/or in vivo (U.S. Pat. No. 4,868,116;  
25 U.S. Pat. No. 5,449,614 and U.S. Pat. No. 6,207,455). Retroviral vectors require target cell division in order to be integrated into the host genome to stably introduce nucleic acid into the cell. Thus, it may be necessary to stimulate replication of the target cell. Successful transductions of hematopoietic stem or progenitor cells with retroviral vectors in an ex vivo setting have been reported. However, Recombinant retroviral vectors can  
30 only accommodate about 8 kb to 10 kb of foreign DNA. This packaging capacity also limits its use in the genetic treatment of DMD.

4. *Lentivirus vectors.* Lentiviruses also belong to the retrovirus family, but they can infect both dividing and non-dividing cells. The best-known lentivirus is the human immunodeficiency virus (HIV), which has been disabled and developed as a vector for in vivo gene delivery. Like the simple retroviruses, HIV has three genes termed *gag*, *pol* and *env*, it also carries genes for six accessory proteins termed *tat*, *rev*, *vpr*, *vpu*, *nef* and *vif*. Using the retrovirus vectors as a model, lentivirus vectors have been made, with the transgene enclosed between the LTRs and a packaging sequence (Naldini et al. *Science* 272, 263-267 [1996]). Some of the accessory proteins can be eliminated without affecting production of the vector or efficiency of infection.

When lentiviral vectors are injected into rodent brain, liver, muscle, eye or pancreatic islet cells, they give sustained expression for over six months. Little is known about the possible immune problems associated with lentiviral vectors. Furthermore, there seems to be no potent antibody response. A major concern about lentiviral vector is its safety in human applications. However, recent development in producing the third generation lentiviral vectors with more deletion in viral genes and improved safety may allow for the general application of lentiviral vectors to in vivo gene therapy.

5. *Adeno-associated viruses (AAV) vectors:* AAV is a naturally occurring defective virus that requires another virus, such as an adenovirus or a herpes virus, as a helper virus for efficient replication and a productive life cycle (Muzyczka et al. *Curr. Topics in Micro. and Immunol.* 158, 97-129 [1992]). AAV vector is the only viral vector system that is based on a non-pathogenic and replication defective virus. It is also one of the few viruses that may integrate its DNA into non-dividing cells, and exhibits a high frequency of stable integration (Flotte et al. *Am. J Respir. Cell. Mol. Biol.* 7, 349-356 [1992]; Samulski et al. *J. Virol.* 63, 3822-3828 [1989]). Vectors containing as little as 300 base pairs of AAV DNA can be packaged.

AAV vectors have been successfully used to establish efficient and long-term gene expression *in vivo* in a variety of tissues without significant immune response or toxicity (Xiao et al. *J. Virol.* 70, 8098-108 [1996]; Kessler et al. *Proc Natl Acad Sci USA* 93, 14082-7 [1996]; Xiao et al. *J Virol* 72, 10222-6 [1998]). Unlike other viral vectors, AAV readily bypasses extracellular barriers due to its small viral particle size (20 nm) that facilitates efficient transduction of muscle myofibers of various maturity (Pruchnic et

al. *Hum Gene Ther* 11, 521-36 [2000]). AAV can also be delivered into a large number of muscle groups via the blood vessels (Greelish et al. *Nat. Med.* 5, 439-443 [1999]) The unparalleled efficiency and safety have led to an increasing interest in AAV-mediated gene therapy for genetic muscle disorders, as well as for metabolic diseases. However, a major obstacle for AAV vectors is the limited packaging size that only allows for genes smaller than 4.7 kb (Song et al. *Proc Natl Acad Sci USA* 95, 14384-8 [1998]; Kay et al. *Nat Genet* 24, 257-261 [2000]), therefore precludes such large gene as dystrophin with a cDNA of 14 kb.

Other viral vector systems that may have application in the subject invention have been derived from vaccinia virus (Chen et al. *J Immunother* 24, 46-57 [2001]), and several RNA viruses. The plus-strand RNA viridae, such as polio (Bledsoe et al. *Nat Biotechnol.* 18, 964-9 [2000]), hepatitis A (Romano G. *Stem Cells*;18, 19-39 [2000]), and sindbis virus (Wahlfors et al. *Gene Ther* 7, 472-80 [2000]) are being developed for high-level gene expression, following either viral infection or delivery of nucleic acids using a nonviral system. These viruses express a replicase protein that can specifically replicate the viral RNA. By inserting a transgene in place of the viral capsid gene(s), it is possible to generate a chimeric RNA that replicates autonomously in the cell and expresses a high level of protein from the plus-coding strand of RNA. These viral vectors are well suited for immunization strategies in which high, transient gene expression is needed to induce an immune response to the transduced cells.

In addition to the viral gene transfer vectors, powerful non-viral gene transfer vectors have also become available for clinical application in the past several years (Ropert et al. *Braz J Med Biol Res.* 32,163-9 [1999]; Lee RJ et al. *Crit Rev Ther Drug Carrier Syst* 14, 173-206 [1997]). These vectors rely on normal mechanisms used by mammalian cells for the uptake and intracellular transport of macromolecules to deliver genetic materials into cells. These vectors include cationic and other liposomes, DNA-viral conjugates, RNA/DNA oligonucleotides and, surprisingly, naked DNA molecules. Physical procedures, such as hydrodynamics-based and electroporation-based procedures have been used to improve gene transfer efficiency of some non-viral vectors (Zhang G. et al. *Gene Ther* 7, 1344-9 [2000]; Yamashita et al. *Cancer Res.* 61, 1005-12 [2001]). Recently, it was also reported that intraperitoneal injection of a  $\beta$ -galactosidase fused to

the protein transduction domain from the human immunodeficiency virus TAT protein resulted in delivery of the fusion protein to all tissues in mice (Schwarze et al. *Science*, 3, 1569-1572 [1999])

Somatic gene transfer using non-viral vectors carrying dystrophin gene have been attempted [Acsadi et al. *Nature* 352, 815-818 [1991]; Rando et al. *Proc. Natl. Acad. Sci USA* 97, 5363-5368 [2000]]. Transgene expression was achieved with only very limited efficiency.

Previous attempts to generate dystrophin minigenes that were shorter than 1/2 of the full-length dystrophin failed to preserve the essential protective functions. Cox et al. and Greenberg et al. reported that expression of Dp 71, a 71 kD non-muscle product of the dystrophin gene that consists of the cysteine-rich and C-terminal domains of dystrophin (exon 63-79), in the skeletal muscle of dystrophin deficient *mdx* mice restored normal levels dystrophin associated proteins (DAPs). However, expression of Dp71 failed to alleviate symptoms of muscle degeneration [Cox et al. *Nature Genet* 8, 333-339 [1994]; Greenburg et al. *Nature Genet* 8, 340-344 [1994]]. Similarly, Yuasa et al (Yuasa et al. *FEBS Lett* 425, 329-336 [1998]; Yamamoto et al. *Hum Gene Ther* 11, 669-80 [2000]) demonstrated that expression of dystrophin minigenes with both intact N- and C-terminal domains and 1 to 3 central rod repeats in mouse skeletal muscle was sufficient to restore DAP complexes but insufficient to restore myofiber morphology and to prevent dystrophic pathology.

## SUMMARY OF THE INVENTION

The present invention provides dystrophin minigenes that are significantly reduced in size without compromising essential functions in protecting muscles from dystrophic phenotypes. The present invention also provides viral vectors carrying the dystrophin minigenes that are capable of mediating efficient and stable correction of both biochemical and physiological defects in a mammalian subject. Furthermore, the present invention provides a method that is more convenient and less time-consuming to discern the dystrophin functional domains *in vivo* and to optimize the minigenes for DMD gene therapy. Finally, the present invention provides a method for treatment of muscular dystrophy.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows the construction of highly truncated dystrophin minigenes and AAV vectors carrying the dystrophin minigene.

FIG. 2a shows immunofluorescent (IF) analysis of the dystrophin and DAP complexes in gastrocnemius muscle of *mdx* muscle at 3-months after treatment with construct AAV-MCK- $\Delta$ 3849 or AAV-MCK- $\Delta$ 3990.

FIG. 2b shows IF analysis of the dystrophin and DAP complexes in gastrocnemius muscle from 15-week old normal C57/B10 mice, from *mdx* mice treated either with vector AAV-MCK- $\Delta$ 3849, AAV-MCK- $\Delta$ 3990 or AAV-MCK- $\Delta$ 4173, or from untreated *mdx* mice.

FIG. 3a shows mini-dystrophin expression in *mdx* mice treated with AAV-MCK- $\Delta$ 3849 at 10 days of age. The animals were sacrificed 6 months post viral injection.

FIG. 3b shows dystrophin expression in untreated 6-month-old *mdx* mice.

FIG. 3c shows mini-dystrophin expression in *mdx* mice treated with AAV-MCK- $\Delta$ 3849 as adult. The animals were sacrificed 2-months post viral injection.

FIG. 3d shows mini-dystrophin expression in *mdx* mice treated with AAV-MCK- $\Delta$ 3990 as adult. The animals were sacrificed 2 months post viral injection.

FIG. 3e shows mini-dystrophin expression in *mdx* mice treated with AAV-MCK- $\Delta$ 3849 as adult. The animals were sacrificed 4 months post viral injection.

FIG. 3f shows mini-dystrophin expression in *mdx* mice treated with AAV-MCK- $\Delta$ 3990 as adult. The animals were sacrificed 4 months post viral injection.

FIG. 3g shows mini-dystrophin expression in *mdx* mice treated with AAV-CMV- $\Delta$ 3849 as adult. The animals were sacrificed 6 months post viral injection.

FIG. 3h shows mini-dystrophin expression in *mdx* mice treated with AAV-CMV- $\Delta$ 3990 as adult. The animals were sacrificed 6 months post viral injection.

FIG. 4a shows protection of muscle plasma membrane integrity by dystrophin minigenes in *mdx* mice treated at 10 days of age.

FIG. 4b shows protection of muscle plasma membrane integrity by dystrophin minigenes in *mdx* mice treated as adult.

FIG. 5a shows the IF analysis of mini-dystrophin expression from construct  $\Delta$ 2796, which contains two rods (rod1 & rod24, see FIG.1). Note that the muscle cell



morphology and central nucleation were not improved after its injection into young mdx mice.

FIG.5b. shows the IF analysis of mini-dystrophin expression from construct CMV-M3, which contains 1 rod (a hybrid rod between rod R1 & rod R24, see FIG.1 and Yuasa et al). Note that the muscle cell morphology and central nucleation were not improved after its injection into young mdx mice.

FIG.6. shows muscle force improvement after AAV-MCK-Δ3990 vector injection into the TA muscle of adult mdx mice. After 10 cycles of lengthening activation the untreated mdx TA muscles (n=8) had only 23% of the force output remaining, while the AAV treated mdx TA muscles (n=8) had nearly 40% of the force output remaining.

## **DETAILED DESCRIPTION AND PREFERRED EMBODIMENTS OF THE INVENTION**

The practice of the present invention will employ, unless other wise indicated, conventional methods of histology, virology, microbiology, immunology, and molecular biology within the skill of the art. Such techniques are explained fully in the literature. All publications, patents and patent applications cited herein, whether supra or infra, are hereby incorporated by reference in their entirety.

As used in this specification and the appended claims, the singular forms "a," "an" and "the" include plural references unless the content clearly dictates other wise.

### **A. Definitions**

In describing the present invention, the following terms will be employed, and are intended to be defined as indicated below.

"Gene transfer" or "gene delivery" refers to methods or systems for reliably introducing a particular nucleotide sequence (e.g., DNA) into targeted cells. The introduced nucleotide sequences may persist in vivo in episomal forms. or integrate into the genome of the target cells. Gene transfer provides a unique approach for the treatment of acquired and inherited diseases, and a number of systems have been developed in the art for gene transfer into mammalian cells. See, e.g., U.S. Pat. No. 5,399,346.

As used herein, the term "effective amount" refers to a level of infection which brings about at least partially a desired therapeutic or prophylactic effect in an organ or

tissue infected by the method of the present invention. The infection with an effective amount of the vector carrying genetic material of interest can then result in the modification of the cellular activities, e.g., a change in phenotype, in an organ or a tissue that has been infected by the method of the present invention. In a preferred  
5 embodiment, the infection with an effective amount of the vector carrying genetic material of interest results in modulation of cellular activity in a significant number of cells of an infected organ or a tissue.

A gene transfer "vector" refers to any agent, such as a plasmid, phage, transposon, cosmid, chromosome, liposome, DNA-viral conjugates, RNA/DNA oligonucleotides,  
10 virus, bacteria, etc., which is capable of transferring gene sequences into cells. Thus, the term includes cloning and expression vehicles, as well as viral and non-viral vectors. A vector may be targeted to specific cells by linking a target molecule to the vector. A targeting molecule is any agent that is specific for a cell or tissue type of interest, including for example, a ligand, antibody, sugar, receptor, or other binding molecule.  
15 The invention is also intended to include such other forms of vectors which serve equivalent functions and which become known in the art subsequently hereto.

An "AAV vector" refers to vectors derived from an adeno-associated virus serotype, including human AAV-1, AAV-2, AAV-3, AAV-4, AAV-5, AAV-6, avian AAV, ovian AAV, etc., and to vectors derived from more than one AAV serotype (hybrid  
20 AAV vectors). For example, a hybrid AAV vector may contain DNA sequences derived from both AAV-1 and AAV-2. An AAV vectors can have one or more of the AAV wild-type genes deleted in whole or part, preferably the rep and/or cap genes, but retain functional flanking ITR sequences. AAV vectors can be constructed using recombinant techniques that are known in the art to include one or more heterologous nucleotide  
25 sequences flanked on both ends (5' and 3') with functional AAV ITRs. In the practice of the invention, an AAV vector can include at least one AAV ITR and a suitable promoter sequence positioned upstream of the heterologous nucleotide sequence and at least one AAV ITR positioned downstream of the heterologous sequence.

A "recombinant AAV vector plasmid" refers to one type of recombinant AAV  
30 vector wherein the vector comprises a plasmid. As with AAV vectors in general, 5' and 3' ITRs flank the selected heterologous nucleotide sequence. AAV vectors can also

include transcription sequences such as polyadenylation sites, as well as selectable markers or reporter genes, enhancer sequences, and other control elements which allow for the induction of transcription. Such control elements are described more fully below. In addition, an "AAV vector" can be stably introduced into a cell line or cell lines for the purpose of viral particle production. Such a cell line is usually termed as AAV packaging cell line.

As used herein, the term "recombinant AAV", "recombinant AAV particle" or "recombinant AAV virion" is defined as an infectious, replication-defective virus composed of an AAV protein shell encapsidating (i.e., surrounding with a protein coat) a heterologous nucleotide sequence, which in turn is flanked 5' and 3' by AAV ITRs. In this regard, single-stranded AAV nucleic acid molecules (either the sense/coding strand or the antisense/anticoding strand as those terms are generally defined) can be packaged into an AAV virion; both the sense and the antisense strands are equally infectious. When the recombinant AAV DNA is equal to or smaller than 50% of the full length viral genome (about 5,000 nucleotides), it can also be packaged as double-stranded hairpin-like DNA into AAV virion. Such virion is also fully infectious.

The term "recombinant AAV particle" or "recombinant AAV virion" also refers to a hybrid AAV particle in which the AAV protein shell and the encapsulated nucleotide sequence may be derived from AAVs of different serotype. For example, a hybrid AAV particle may contain AAV-1 capsid proteins and AAV-2 ITRs, or vice versa. It is also possible to create hybrid AAV capsid proteins using coding sequences from two or more AAV capsid genes. In addition, the capsid protein of a recombinant AAV may be manipulated by mutation, deletion, and/or insertion of amino acid sequence in order to modify the tropism of the recombinant AAV (Wu et al. *J. Virol* 74, 8635-47 [2000]; Girod et al. *Nat Med* 5, 1052-1056 [1999]).

A number of techniques for constructing recombinant AAV are known in the art. See, e.g., U.S. Pat. No. 5,173,414, Lebkowski et al. *Mol Cell Biol* 8, 3988-3996 [1988]; Carter BJ, *Current Opinion in Biotechnology* 3, 533-539 [1992]; Muzyczka N, cited supra; and Zhou et al. *J. Exp. Med.* 179, 1867-1875 [1994]; Xiao et al. *J. Virol.* 72, 2224-32 [1998].

The term "expression control element" or "regulatory element" refers collectively to promoter sequences, polyadenylation signals, transcription termination sequences, upstream regulatory domains, origins of replication, internal ribosome entry sites ("IRES"), enhancers, and the like, which collectively provide for the replication,

5 transcription and translation of a coding sequence in a recipient cell. Not all of these control sequences need always be present so long as the selected coding sequence is capable of being replicated, transcribed and translated in an appropriate host cell. The term "promoter" is used herein in its ordinary sense to refer to a DNA regulatory sequence that are sufficient for RNA polymerase recognition, binding and transcription  
10 initiation. Additionally, a promoter includes sequences that modulate the recognition, binding and transcription initiation activity of RNA polymerase. Such sequences may be cis acting or may be responsive to trans acting factors. Depending upon the nature of the regulation, promoters may be constitutive or regulated. Examples of promoters are SP6, T4, T7, SV40 early promoter, cytomegalovirus (CMV) promoter, mouse mammary tumor  
15 virus (MMTV) steroid-inducible promoter, Moloney murine leukemia virus (MMLV) promoter, phosphoglycerate kinase (PGK) promoter, muscle creatine kinase (MCK) promoter, myosin promoter,  $\alpha$ -actin promoter and the like. Alternatively, the modified versions of the above promoters and even the synthetic muscle promoters (Li et al. *Nat Biotechnol* 17, 241-245, [1999]) may be included. Finally, the promoter may be an  
20 endogenous AAV promoter or AAV inverted terminal repeat (ITR).

The term "transduction" denotes the delivery of a DNA molecule to a recipient cell either in vivo or in vitro, via a replication-defective viral vector, such as via a recombinant AAV virion.

The term "muscle cell" or "tissue" refers to a cell or group of cells derived from  
25 muscle, including but not limited to cells and tissue derived from skeletal muscle; cardiac muscle, smooth muscle, e.g., from the digestive tract, urinary bladder and blood vessels.. The term captures muscle cells both in vitro and in vivo. Thus, for example, an isolated cardiomyocyte would constitute a "muscle cell" for purposes of the present invention, as would a muscle cell as it exists in muscle tissue present in a subject in vivo. The term  
30 also encompasses both differentiated and nondifferentiated muscle cells, such as myocytes, myotubes, myoblasts, cardiomyocytes and cardiomyoblasts, and progenitor

cells, for example, the muscle derived stem cells or the bone marrow derived stem cells that can become muscle cells after differentiation

“Operably linked” refers to an arrangement of elements wherein the components so described are configured so as to perform their usual function. Thus, control elements operably linked to a coding sequence are capable of effecting the expression of the coding sequence. The control elements need not be contiguous with the coding sequence, so long as they function to direct the expression thereof. Thus, for example, intervening untranslated yet transcribed sequences can be present between a promoter sequence and the coding sequence and the promoter sequence can still be considered “operably linked” to the coding sequence.

The term “dystrophin minigene” refers to the novel dystrophin constructs created by extensive deletions in the central rod domain plus extensive deletion in the C-terminal domain of the human dystrophin cDNA. In addition, the dystrophin minigenes may contain a modified N-terminal domain in which DNA sequences surrounding the original protein translation initiation codon ATG are modified. The modified sequences enhance the mini-dystrophin protein synthesis. Alternatively, the dystrophin minigene may be a hybrid gene in which some of the domains are substituted with homologous domains from utrophin or spectrin genes (Tinsley et al, *Nature* 360, 591-593 [1992]; Koenig et al. *Cell* 53, 219-216 [1988]). In particular, utrophin is highly homologous to dystrophin in both structure and functions, so that their major domains should be interchangeable (Tinsley et al, *Nature*. 384, 349-353 [1996]; Deconinck et al, *Nat Med.* 3, 1216-21 [1997]; Rafael et al *Nat Genet.* 19, 79-82 [1998];). For example, the N-terminal and/or the C-terminal domains of dystrophin may be substituted with the utrophin counterparts in the dystrophin minigenes. Similarly, the central rod domain may consist of rod repeats from utrophin or spectrin genes. The dystrophin minigenes are smaller than the 5 kb packaging limit of AAV viral vectors. Furthermore, it is also plausible to construct a minigene of utrophin in a similar fashion as of the dystrophin minigene described in this invention. Because some DMD patients completely lack the dystrophin protein, the dystrophin minigene product may be a neo-antigen. Substitution of dystrophin domains with those of utrophin may lower immune responses.

The term "mini-dystrophin" refers to the polypeptides encoded by the dystrophin minigenes. Most importantly, the mini-dystrophins harbor biological functions that can protect the muscle from dystrophic pathology and symptoms.

5 The symbol "Δ" (delta) is a prefix for the dystrophin minigenes that contain deletions as described above.

By "mammalian subject" is meant any member of the class Mammalia including, without limitation, humans and nonhuman primates such as chimpanzees and other apes and monkey species; farm animals such as cattle, sheep, pigs, goats and horses; domestic mammals such as dogs and cats; laboratory animals including rodents such as mice, rats  
10 and guinea pigs, and the like. The term does not denote a particular age or sex. Thus, adult and newborn subjects, as well as fetuses, whether male or female, are intended to be covered.

The term "expression cassette" refers to a construct of genetic material that contains coding sequences and enough regulatory information to direct proper  
15 transcription and translation of the coding sequences in a recipient cell.

### **B. Detailed description of the invention**

To explore the feasibility of using viral vectors for DMD gene therapy, we have devised strategies to create novel dystrophin minigenes, which are small enough to be packaged into retrovirus or AAV vectors, and yet retain the essential functions needed for  
20 protecting muscle from the pathological symptoms. We have created minigenes in which up to 75% of the central rod domain (20 of the 24 rods; 2 of the 4 hinges), as well as nearly all the C-terminal domain (exons 71-78), are deleted (FIG. 1). These novel dystrophin minigenes, as small as only one third (1/3) of the 11 kb full-length dystrophin coding sequence, are significantly smaller than the 6.3 kb Becker-form mini-dystrophin  
25 gene (England et al. *Nature* 343, 180-2 [1990]) that was widely used in transgenic and gene therapy studies in *mdx* mice. The minigene comprises the N-terminus sequence of the dystrophin gene, the C-terminal cysteine-rich (CR) domain of the dystrophin gene, at least hinges H1 and H4 of dystrophin gene, and at least four rod repeats. The rod repeats may be chosen from the rod repeats of dystrophin, utrophin or spectrin genes, preferably  
30 from the 24 rod repeats of dystrophin gene, and most preferably from the group consisting of rod repeats R1, R2, R3, R22, R23 and R24 of dystrophin gene. The N-

terminus of the dystrophin minigene may be modified to improve expression efficiency without affecting the functionality of the gene product. For example, the original sequence surrounding the translation initiation ATG codon of the dystrophin gene may be substituted by the Kozak sequence to increase the efficiency of protein synthesis. In one embodiment of the current invention, the three nucleotides upstream of the coding sequence may be changed from "AAA" to "CCA" and the fourth nucleotide in the coding sequence may be changes from "C" to "G". In addition, a portion or the entire N-terminus may be substituted by its counterpart of the utrophin gene. Similarly, the CR domain of the dystrophin minigene can also be substituted by its counterpart of the utrophin gene.

The dystrophin minigenes may be introduced into a mammalian subject using a variety of methods. It may be introduced into the subject in an expression cassette as a naked DNA with or without hydrodynamic-based or electroporation-based procedures. It may be introduced into the subject using non-viral vectors such as liposomes or virus-liposome complexes, or with viral vectors such as adenovirus, HSV, baculovirus, retrovirus, lentivirus, and preferably AAV. Expression of the dystrophin minigenes may be controlled by a number of regulatory elements, including but not limited to, AAV inverted terminal repeat (ITR), retrovirus long terminal repeat (LTR), cytomeglovirus (CMV) immediate early promoter and/or enhancer, CMV enhancer and chicken  $\beta$ -actin promoter (CB promoter),  $\alpha$ -actin promoter, myosin promoter, muscle-specific creatine kinase (MCK) promoter and/or enhancer, and the like. Alternatively, the modified versions of the above promoters and the synthetic muscle promoters (Li et al. cited supra) etc. may also be used.

Expression of dystrophin minigene may be detected by immunofluorescent staining and immunoblotting (Western blotting). The functionality of mini-dystrophin may be examined by determining whether the mini-dystrophins are capable of restoring the missing DAP complexes on the myofiber plasma membrane, including the sarcoglycan complex which is not found in untreated dystrophic muscle due to the primary deficiency of dystrophin. To further investigate the functionality of the novel mini-dystrophins, it is essential to demonstrate that they can protect muscle from the pathological phenotypes. The onset of the pathology in *mdx* mice starts at around three

weeks of age with massive waves of myofiber degeneration/regeneration. This process is characterized by the presence of central nuclei in myofibers, a primary pathological sign of muscular dystrophies. The absence or reduction of central nucleation after gene therapy would suggest that the therapy is successful. The position of nuclei in a muscle fiber may be determined by DAPI staining or H & E staining.

Muscle cryosections of 8  $\mu$ m thickness may be immunofluorescently stained with the Mouse-on-Mouse Kit from the Vector Laboratories (Burlingame, CA) according to the manufacturer's protocol, except that the cryosections may be immediately treated with the blocking buffer without the fixation step (Li et al. *Gene Ther* 6, 74-82 [1999]).

Monoclonal antibodies against dystrophin (NCL-Dys3 and NCL-Dys2) and against  $\alpha$ -,  $\beta$ -, and  $\gamma$ -sarcoglycans (NCL- $\alpha$ -SARC, NCL- $\beta$ -SARC and NCL- $\gamma$ -SARC) may be purchased from Novocastra Laboratories Ltd (Burlingame, CA). Muscle cell nuclei may be counterstained with 0.01% DAPI (Sigma, St. Louis, MO) for 10 minutes. Photographs may be taken with a Nikon TE-300 fluorescent microscope.

Plasma membrane damage and leakage in dystrophic muscle is a major physiological defect and also a major pathological cause. To determine whether AAV mini-dystrophin treatment would be effective in protecting plasma membrane from mechanical damage, myofiber membrane integrity test may be performed by intravenous injection of Evans Blue dye. Evans Blue is a widely used vital red-fluorescent dye that is excluded by the healthy myofibers, but is taken up by the dystrophic myofibers containing leaky cell membrane due to contractile damages. A previous study of *mdx* mice revealed that the apoptotic myonuclei were mostly found in Evans Blue dye positive myofibers, thus correlating plasma membrane leakage and muscle cell apoptosis (Matsuda et al. *J Biochem (Tokyo)* 118, 959-64 [1995]).

Evans Blue dye (10 mg/ml in PBS) may be injected into the tail vein of C57/B10 mice, *mdx* mice, and AAV vector-treated *mdx* mice at the dose of 0.1 mg/gram of body weight. Following dye injection, mice may be allowed continuous swimming for 20 minutes. At 15 hours after Evans Blue injection, muscles may be collected and cryosectioned. Evans Blue dye positive myofibers may be observed under the fluorescent microscope with Rhodamine filters.



Muscle constrectile force improvement was evaluated in the mdx mice after treatment with AAV vectors containing the dystrophin minigene. Tibialis anterior (TA) muscles of 2 to 3 month old mdx mice were injected with AAV-MCK-3990 vector. The injection was given in such a way that one leg was treated while the other leg in the same animal was left untreated. The latter was used as a control. At 6 months after AAV treatment, the mdx mice were anesthetized with pentobarbital sodium (70mg/kg, i.p.) and the entire TA muscle was removed and mounted in a vertical tissue chamber for in vitro force measurement. The muscle was stimulated (Grass model S-88 stimulator and current amplifier) by use of monophasic rectangular pulses of cathodal current (1.0-ms duration). Maximum tetanic force ( $P_o$ ) was assessed using a stimulation frequency of 75 pps delivered in a 500 ms duration train. Following the determination of  $P_o$ , the ability of the TA muscle to sustain force generation during repetitive lengthening activations (which should induce maximal damage to the muscle) was assessed. Peak force measured prior to lengthening was termed  $P_{ISO}$ . Subsequently, the muscle was lengthened at a constant velocity of 1.0  $L_o/s$  from 100 to 110%  $L_o$ . Stimulus trains were repeated every 2-min (duty cycle 0.004) for a total of 10 cycles. Changes in  $P_{ISO}$  were used to index impairment of muscle function associated with the damages caused by lengthening activations.

### C. Preferred embodiments

The following examples are meant merely to exemplify several embodiments, and should not be interpreted as limiting the scope of the claims, which are delimited only by the specification.

#### *Example 1*

#### *Dystrophin minigenes and AAV vectors carrying the minigenes*

This example describes the construction of highly truncated dystrophin minigenes and AAV vectors carrying the minigenes. The dystrophin minigene constructs were made mainly by PCR cloning method using Pfu polymerase (Stratagene, CA) and human dystrophin cDNA (GenBank # NM 004006) as the template. For consistency, the numbering of the nucleotide only includes the 11,058 bp dystrophin protein coding sequence (SEQ ID NO:1).

As depicted in FIG. 1, dystrophin minigene  $\Delta 4173$  (SEQ ID NO:2) contains nucleotides 1-1992 (N-terminus, hinge H1 and rods R1, R2 & R3, SEQ ID NO:3) and 8059-10227 (rods R22, R23 & R24, hinge H4 and CR domain, SEQ ID NO:4) and 11047-11058 (the last 3 amino acids of dystrophin, SEQ ID NO:5).

5        Dystrophin minigene  $\Delta 3990$  (SEQ ID NO:6) contains nucleotides 1-1668 (N-terminus, hinge H1 and rods R1 & R2, SEQ ID NO:7), 7270-7410 (hinge H3, SEQ ID NO:8), 8059-10227 (rods R22, R23 & R24, hinge H4 and CR domain, SEQ ID NO:4) and 11047-11058 (the last 3 amino acids of dystrophin, SEQ ID NO:5).

10       Dystrophin minigene  $\Delta 3849$  (SEQ ID NO:9) contains nucleotides 1-1668 (N-terminus, hinge H1 and rods R1 & R2, SEQ ID NO:7), 8059-10227 (rods R22, R23 & R24, hinge H4 and CR domain, SEQ ID NO:4), and 11047-11058 (the last 3 amino acids of dystrophin, SEQ ID NO:5).

15       Dystrophin minigene  $\Delta 3531$  (SEQ ID NO:10) contains nucleotide 1-1341 (N-terminus, hinge H1 and rods R1, SEQ ID NO:11), 8059-10277 (rods R22, R23 & R24, hinge H4 and CR domain, SEQ ID NO:4), and 11047-11058 (the last 3 amino acids of dystrophin, SEQ ID NO:5).

20       Dystrophin minigene  $\Delta 3510$  (SEQ ID NO:12) contains nucleotide 1-1668 (N-terminus, hinge H1 and rods R1 & R2, SEQ ID NO:7), 8407-10277 (rods R23 & R24, hinge H4 and CR domain, SEQ ID NO:13) and 11047-11058 (the last 3 amino acids of dystrophin, SEQ ID NO:5).

25       Dystrophin minigene  $\Delta 3447$  (SEQ ID NO:14) contains nucleotide 1-1992 (N-terminus, hinge H1 and rods R1, R2 & R3, SEQ ID NO:3), 8794-10277 (rod R24, hinge H4 and CR domain, SEQ ID NO:15) and 11047-11058 (the last 3 amino acids of dystrophin, SEQ ID NO:5).

The above constructs were made by blunt-end ligation of the Pfu amplified PCR products of each individual segment, so that all the protein coding sequences are precisely spliced together in frame. The PCR primers used in the reactions are listed in Table 1:

5 Table 1. PCR primers used in the cloning of dystrophin fragments

Primer Names		Primer Sequence(5'-3')	Sequence position	
<u>Forward primers:</u>				
10	F1 (ATG-A)	ATTTTCACCATGGTTTGGTGGGAAGAAG	1-19 (28bp)	SEQ ID NO:16
	F2 (H3-1)	CAGCCTGACCTAGCTCCTGGACTGA	7270-7294 (25bp)	SEQ ID NO:17
	F3 (R22-1)	ACTCATAGATTACTGCAACAGTTCC	8059-8083 (25bp)	SEQ ID NO:18
	F4 (R23-1)	AGTTCTGACCAGTGGGAAGCG	8407-8427 (20 bp)	SEQ ID NO:19
	F5 (R24-1)	ACCCTTGAAAGACTCCAGGAAC	8794-8816 (22 bp)	SEQ ID NO:20
<u>Reverse primers:</u>				
15	R1 (R1-2)	TCTATGTAAATTGCTTTGTT	1341-1361 (20 bp)	SEQ ID NO:21
	R2 (R2-2)	GTCTTGTAAGAAGAACCCAGCGGTCT	1668-1644 (25bp)	SEQ ID NO:22
	R3 (R3-2)	CTGTGCTGTACTCTTTTCAAGTTTT	1992-1968 (25bp)	SEQ ID NO:23
	R4 (H3-2)	AGGTACCTCCAACATCAAGGAAGAT	7410-7386 (25bp)	SEQ ID NO:24
	R5 (Tail-2A)	CTACATTGTGTCTGGGAGTTTCCATGTTGTC	11058-11047, 10227-10210(30bp)	SEQ ID NO:25
20				

The dystrophin minigenes were then subcloned into an AAV vector plasmid (SEQ ID NO:26) containing an MCK promoter, a 595 bp Hind III/BstE II fragment from plasmid p(+enh206) 358MCKCAT ( Shield et al. *Mol Cell Biol* 16, 5058-68 [1996]), and a 60 bp small polyA signal sequence, resulting in AAV vector constructs AAV-MCK- $\Delta$ 4173 (SEQ ID NO:27), AAV-MCK- $\Delta$ 3990 (SEQ ID NO:28), AAV-MCK- $\Delta$ 3849 (SEQ ID NO:29), AAV-MCK-3531 (SEQ ID NO:30), AAV-MCK-3510 (SEQ ID NO:31) and AAV-MCK-3447 (SEQ ID NO:32).

Similarly, the dystrophin minigenes were also cloned into an AAV vector plasmid (SEQ ID NO:33) containing a CMV promoter (620 bp) and the small polyA signal sequence, resulting in AAV vector constructs AAV-CMV- $\Delta$ 3990 (SEQ ID NO:34), AAV-CMV- $\Delta$ 3849 (SEQ ID NO:35). In addition, the dystrophin minigene  $\Delta$ 3849 was cloned into an AAV vector plasmid containing an MCK enhancer, a CMV promoter, and

the small polyA signal sequence, resulting AAV vector construct AAV-E-CMV-3849 (SEQ ID NO:36).

The recombinant viral vector stocks were produced precisely according to the three-plasmid co-transfection method as described by Xiao et al. (cited supra). The AAV viral vectors were subsequently purified twice through CsCl density gradient ultracentrifugation using the previously published protocols (Snyder et al. in *Current Protocols in Human Genetics*, eds. Dracopoli et al. [John Wiley & Sons Ltd., New York], pp. 12.1.1-12.2.23. [1996]). The vector titers of viral particle number were determined by DNA dot blot method (Snyder et al. cited supra), and were approximately  $5 \times 10^{12}$  genome copies (GC) per ml.

### **Example 2**

#### **Restoration of DAP complexes**

This example describes whether dystrophin minigene products still retain the major biochemical functionality including submembrane localization and interaction with dystrophin associated protein (DAP) complexes. Healthy *C57/B10* mice and dystrophic *mdx* mice were purchased from The Jackson Laboratory (Bar Harbor, Maine). Ten-day old *mdx* pups or 50-day old *mdx* adult mice were injected into the hindleg gastrocnemius muscle with 50  $\mu$ l ( $5 \times 10^{10}$  GC) of different AAV mini-dystrophin vectors.

At three months and six months after vector injection, the muscles were collected for evaluation of mini-dystrophin expression and biochemical restoration of the DAP complexes, which were absent due to the primary deficiency of dystrophin. IF staining on thin sections of AAV treated muscles, using an antibody (Dys3) specific to human dystrophin, revealed widespread vector transduction and correct submembrane location of the mini-dystrophins in a majority of the myofibers, especially in muscles treated with AAV vectors containing dystrophin minigene  $\Delta$ 3849 or  $\Delta$ 3990 (FIG. 2a & 2b; FIG. 3a). As expected, the equivalent muscle from the age-matched healthy *C57/B10* mice showed indistinguishable dystrophin staining pattern, when stained with an antibody (Dys2) that recognizes both mouse and human dystrophin C-terminal region (FIG. 2b). As expected, this antibody (Dys2) failed to stain the AAV treated *mdx* muscle due to deletion of the C-terminal region in our dystrophin minigenes (data not shown). This result further confirmed the identity of mini-dystrophins that were derived from the AAV vectors.

Consistently, the untreated *mdx* control muscle showed no dystrophin staining (FIG. 2b) except the very few somatic revertant myofibers recognized by Dys2 antibody.

Furthermore, injection of AAV mini-dystrophin vectors into the adult *mdx* muscle (gastrocnemius) showed similar results when examined for dystrophin expression at 2 and 4 months after injection of AAV MCK vectors (FIG. 3c-3f), or at 6 months after injection of AAV CMV vectors (FIG. 3g and 3h). Importantly, there was no cytotoxic T-lymphocyte (CTL) destruction against the myofibers that persistently expressed mini-dystrophins of human origin from AAV vectors, either driven by a CMV promoter or by a muscle-specific MCK promoter.

Immunofluorescent staining using three antibodies against  $\alpha$ ,  $\beta$ , and  $\gamma$  sarcoglycans respectively, showed positive results in all of the consecutive thin sections adjacent to those stained with dystrophin antibodies (FIG. 2b). These results provided evidence of biochemical functionality of the mini-dystrophins, which lack the C-terminal domain but are still capable of interacting with the DAP complexes.

### **Example 3**

#### ***Amelioration of dystrophic pathology***

This example demonstrates that dystrophin minigene products can protect muscle from the pathological phenotypes. The onset of the pathology in *mdx* mice starts at around three weeks of age with massive waves of myofiber degeneration/regeneration.

This process is characterized by the presence of central nuclei in myofibers, a primary pathological sign of muscular dystrophies. The absence or reduction of central nucleation after gene therapy would suggest that the therapy is successful. Therefore, we initially chose to test the AAV mini-dystrophin constructs in young *mdx* mice (10-day old) before the onset of central nucleation, to see whether muscle degeneration/regeneration can be prevented.

Histological examination of the *mdx* muscles at 3 and 6 months after AAV mini-dystrophin (containing more than 2 rod domains) treatment, which was prior to the onset of central nucleation, showed nearly exclusive (~98%) peripheral nucleation in the mini-dystrophin positive myofibers, as revealed by dystrophin immunostaining and myonuclei counterstaining with DAPI (FIG. 2a, FIG. 2b first column; FIG. 3a and Table 2). The mutual exclusivity between mini-dystrophin expression and central nucleation in the

vector treated *mdx* muscle precisely mirrored that of the normal muscle (FIG. 2b and Table 2). In addition, the myofibers positive for mini-dystrophin expression also exhibited consistent myofiber sizes and polygonal shapes indistinguishable from those of the normal muscle (FIG. 2a and 2b). By contrast, the untreated *mdx* muscle showed extensive (75.4%) central nucleation (Table 2)), with additional signs of dystrophic pathology including wide variation of myofiber sizes, round myofiber shapes, and fibrosis (FIG. 2b). Noticeably, the *mdx* muscle treated with constructs  $\Delta 2796$  and M3 (containing 2 rods and 1 rod, respectively, see FIG.1.) showed the same morphology as the untreated *mdx* muscle, except for the positive IF staining of the mini-dystrophin, which is not functional in terms of improving muscle morphology, pathology and preventing muscle degeneration/regeneration and central nucleation (FIG.5a & 5b and Table 2). Hence, treatment of dystrophic muscle by AAV vector with minigenes containing more than 2 rods (See FIG.1.) prevented dystrophic pathology and led to normal histology in terms of peripheral nucleation, consistent myofiber size and lack of fibrosis in the mini-dystrophin positive areas. These results unequivocally demonstrated the absence of muscle degeneration due to the therapeutic effects of the novel mini-dystrophins in young *mdx* mice.

We subsequently tested AAV vectors containing dystrophin minigenes with more than 2 rods in treating adult *mdx* mice (45 days of age) after the onset of massive waves of degeneration/regeneration, to see whether the pathological process can be stopped or reversed. At the time of vector injection, a majority (~75%) of the myofibers already underwent degeneration/regeneration process and displayed central nucleation. At 2 months, 4 months and 6 months after AAV mini-dystrophin injection, widespread dystrophin expression was observed accompanied by normal myofiber morphology and lack of fibrosis in the dystrophin positive areas (FIG. 3a and 3b). By contrast, muscle of untreated *mdx* mice (FIG. 3b), or areas of treated muscle without successful vector gene transfer, manifested progressive degeneration and fibrosis. In addition, a reduction of central nucleation in mini-dystrophin positive myofibers was observed (from approximately 75% before vector treatment to 35-50% after vector treatment; see Table 2). The partial reversal of central nucleation was also observed in healthy mouse muscle, where a majority of the myonuclei remained centrally located once experiencing a

transient pathology such as myotoxin treatment (Martin et al. *Muscle Nerve* 11:588-96 [1988]). Persistence of central nucleation was also observed after treatment of adult *mdx* muscle with a gutless adenovirus vector containing the full-length dystrophin cDNA.

Based on the above observations, our novel mini-dystrophin genes (containing more than 2 rods) demonstrated therapeutic effects in ameliorating dystrophic pathology in both young and adult *mdx* muscles.

#### **Example 4**

##### ***Protection of myofiber membrane integrity***

This example demonstrates that mini-dystrophins containing more than 2 rods (see FIG. 1.) are capable of protect myofiber membrane integrity. Initially, Evans Blue was administered into the tail vein of *mdx* mice that were treated at young age (10-day old) with AAV vectors three months before. The age-matched untreated *mdx* mice and healthy C57/B10 mice were used as controls. To induce mechanical stress, the mice were allowed to exercise by continuous swimming for 20 minutes. Muscles were then collected and examined for dystrophin expression as well as for Evans Blue dye uptake. As expected, muscle from healthy mice revealed uniform dystrophin staining across the muscle sections and no uptake of the dye by the myofibers (FIG. 4a, top row). The AAV vector treated *mdx* muscle showed results consistent with the healthy muscle, thus mutual exclusivity of dystrophin expression and dye uptake (FIG. 4a, second to fourth rows). Dye uptake (red fluorescence) was found only in myofibers that lacked mini-dystrophin expression in the areas not transduced by AAV vectors (FIG. 4a, 2<sup>nd</sup>, 3<sup>rd</sup> & 4<sup>th</sup> rows). By contrast, the untreated *mdx* muscle revealed absence of dystrophin and extensive dye uptake (FIG. 4a, bottom row). More importantly, AAV mini-dystrophin treatment of adult *mdx* muscle also achieved similar results in protecting myofibers from plasma membrane leakage when analyzed at 2 months and 6 months after vector injection (FIG. 4b). These results unequivocally demonstrated the physiological functionality of the novel mini-dystrophins in maintaining membrane integrity and protecting myofibers from mechanical damages in both young and adult *mdx* mice.

Table 2. AAV mini-dystrophin gene transfer in young and adult *mdx* mice

	Animals * & vectors	n	Age at Vector injection	Months post injection	% Dystrophin positive fibers	% Central nuclei**
10	<i>mdx</i> +Δ3510	4	12 days	3	35 ~ 80	1.06 (68/6413)
	<i>mdx</i> +Δ3531	4	12 days	3	25 ~ 40	1.72 (37/2140)
	<i>mdx</i> +Δ3849	4	10 days	3	56 ~ 88	1.02 (72/7098)
	<i>mdx</i> +Δ3990	4	10 days	3	50 ~ 80	0.99 (56/5652)
	<i>mdx</i> +Δ4173	4	10 days	3	15 ~ 25	0.93 (26/2791)
15	<i>mdx</i> +Δ3849	4	10 days	6	40 ~ 60	2.80 (51/1824)
	<i>mdx</i> +Δ3990	2	10 days	6	35 ~ 45	2.30 (34/1478)
	<i>mdx</i> +Δ3849	2	50 days	2	35 ~ 50	34.76 (510/1467)
	<i>mdx</i> +Δ3990	2	50 days	2	35 ~ 40	34.18 (685/2004)
	<i>mdx</i> +Δ3849	4	50 days	4	20 ~ 25	44.24 (615/1390)
20	<i>mdx</i> +Δ3990	4	50 days	4	20 ~ 30	46.18 (695/1505)
	<i>C57/B10</i>	4	No injection	N/A	100	1.45 (56/3860)
	<i>mdx</i>	4	No injection	N/A	<1	75.4 (2382/3160)
25	<i>mdx</i> +Δ2796	4	12 days	3	30 ~ 45	72 (3888/5400)
	<i>mdx</i> +M3	8	10-12 days	3	20 ~ 65	81 (5589/6900)

Note: \* Untreated control *mdx* and C57/B10 mice were about 3 months old at the endpoints of experiments. AAV vectors were driven by a MCK promoter.

30 \*\* All numbers were collected from dystrophin-positive myofibers which were photographed following immunofluorescent staining and DAPI counterstaining, except in



untreated *mdx* mice which had extensive central nucleation and very few dystrophin-positive

5

### ***Example 5***

#### ***Restoration of muscle strength***

This example demonstrates that mini-dystrophins restore muscle strength in *mdx* mice. Muscle contractile force improvement was evaluated in the *mdx* mice after treatment with AAV vectors containing the dystrophin minigene. Tibialis anterior (TA) muscles of 2 to 3 month old *mdx* mice were injected with AAV-MCK-3990 vector. The injection was given in such a way that one leg was treated while the other leg in the same animal was left untreated. The latter was used as a control. At 6 months after AAV treatment, the *mdx* mice were anesthetized and the entire TA muscle was removed and mounted in a vertical tissue chamber for in vitro force measurement. The muscle was stimulated by the use of monophasic rectangular pulses of cathodal current (1.0-ms duration). Maximum tetanic force ( $P_o$ ) was assessed using a stimulation frequency of 75 pps delivered in a 500 ms duration train. Following the determination of  $P_o$ , the ability of the TA muscle to sustain force generation during repetitive lengthening activations (which should induce maximal damage to the muscle) was assessed. Peak force measured prior to lengthening was termed  $P_{ISO}$ . Subsequently, the muscle was lengthened at a constant velocity of 1.0  $L_o/s$  from 100 to 110%  $L_o$ . Stimulus trains were repeated every 2-min (duty cycle 0.004) for a total of 10 cycles. Changes in  $P_{ISO}$  were used to index impairment of muscle function associated with the damages caused by lengthening activations. As shown in Figure 6, after 10 cycles of lengthening activations the untreated TA muscles (n=8) had only 23% of the force output remaining, while the AAV treated TA muscles (n=8) had nearly 40% of the force output remaining. This result strongly indicates that the dystrophin minigene can protect the muscle from mechanical force induced damage, therefore, restore the muscle strength.

In summary, these examples demonstrate that dystrophin gene can be successfully reduced to one third (1/3) of its 11 kb full-length coding sequence, without

compromising essential functions in protecting muscles from dystrophic phenotypes. Moreover, we have demonstrated for the first time that intramuscular injection of AAV vectors carrying the novel human dystrophin minigenes can achieve efficient and long-term therapeutic effects in a mammalian animal model. Long-term correction of both biochemical and physiological defects in the dystrophic muscles was realized by the persistent mini-dystrophin expression from AAV vectors, and the apparent lack of CTL immune response against myofibers expressing human dystrophin.

### ***Example 6***

#### ***Construction and testing of retroviral vectors***

10 Retrovirus based gene transfer vectors are widely used to introduce transgenes permanently into the in vitro cultured cells. Those target cells may be stable cell lines or primary cell cultures derived from freshly isolated tissues or bone marrow. Some of the primary cell cultures may contain progenitor cells or stem cells, for example, hematopoietic stem cells and muscle derived stem cells. Those stem cells possess the  
15 capability of differentiating into mature muscle cells, i.e. myotubes and myofibers. Therefore, ex vivo gene transfer of the dystrophin minigenes via the retroviral vector may be a useful method to treat muscular dystrophin by infecting the stem cells isolated from the patients, who lack the dystrophin protein due to mutations in the dystrophin gene. To examine the usefulness of retroviral vectors, we cloned dystrophin minigene  $\Delta 3990$  or  
20  $\Delta 3849$  (PCR product) into the Stu I site of a retroviral vector plasmid pLNCX (Clontech, California, USA). Two retroviral vector plasmids were obtained respectively carrying dystrophin minigene  $\Delta 3990$  or  $\Delta 3849$  under the control of a CMV promoter. The retroviral vector particles were produced by transfecting the vector plasmid pLNCX- $\Delta 3990$  or pLNCX $\Delta 3849$  into the packaging cell line AmphoPack 293 (Clontech,  
25 California, USA). The above retrovirus particles were used to infect the myoblast cells isolated from the muscle tissue of mdx mice. Selection drug G418 was used to kill the cells not infected by the retroviral vector, which carried a Neo<sup>r</sup> gene to confer the G418 resistance. The G418 resistant myoblast cells containing the  $\Delta 3990$  or  $\Delta 3849$  minigene were induced to differentiation into myotubes by culturing with 2% horse serum in  
30 DMED media. The differentiated myotubes were subjected to immunofluorescent staining using monoclonal antibody (Dys-3) against the minigene protein product. A